MEMS MICRO-VALVE FOR SPACE APPLICATIONS

I. Chakraborty, W.C. Tang, D.P. Bame, T.K. Tang
Jet Propulsion Laboratory (JPL)
4800 Oak Grove Drive, Pasadena, CA91109-8099
phone: 818-354-3672 fax: 818-393-4663 email: Indrani.Chakraborty@jpl.nasa.gov

ABSTRACT

We report on the development of a Micro-Electro-Mechanical Systems (MEMS) valve that is designed to meet the rigorous performance requirements for a variety of space applications, such as micro-propulsion, in-situ chemical analysis of other planets, or micro-fluidics experiments in micro-gravity. These systems often require very small yet reliable silicon valves with extremely low leak rates and long shelf lives. Also, they must survive the perils of space travel, which include unstoppable radiation, monumental shock and vibration forces, as well as extreme variations in temperature. Currently, no commercial MEMS valve meets these requirements. We at JPL are developing a piezoelectric MEMS valve that attempts to address the unique problem of space. We begin with proven configurations that may seem familiar. However, we have implemented some major design innovations that should produce a superior valve. The JPL micro-valve is expected to have an extremely low leak rate, limited susceptibility to particulates, vibration or radiation, as well as a wide operational temperature range.

INTRODUCTION

MEMS have always had huge potential applications for space. Any reduction in mass or power required for a space instrument or subsystem results in an exponential savings for launch cost as well as a significant increase in mission lifetime. It is a cry for MEMS if ever there was one. Unfortunately, no NASA project engineer will embrace a smaller subsystem if it means a sacrifice of performance, and certain aspects of MEMS have yet to rise to the occasion.

Table 1: Valve Requirements for NASA deep Space Miniature Spacecraft Propulsion

	Valve
Leak Rate	< 0.3 scc/hr Helium
Actuation Speed	< 10 milliseconds
Inlet Pressure	0 – 400 psia
Shock	3000 G at 10 kHz
Vibration	31.5 G_{rms} for 3 min
Temperature	-120 °C to 200 °C
Radiation	50 krad/year
Particulates	1.0 micron

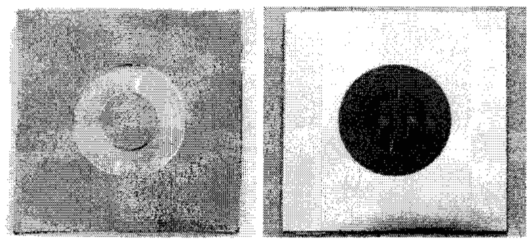


Figure 1: Finished Diaphragm and Seat Parts

MEMS fluidics and sensors have come a long way. Unfortunately, MEMS control actuators have not kept up. For example, very complicated yet precise analysis for life can be done on a silicon chip. However, we have yet to find a silicon valve that can keep the chamber sealed and the reagents from subliming away during the journey to Mars. We can implement the entire propulsion system for a small spacecraft in silicon, yet have no way of controlling the flow of the propellants. Indeed, NASA has identified a low-leak space qualified regulator valve as a key technology for enabling micro-instruments and micro-spacecraft, the future of space exploration.

Valve requirements for a typical micro-spacecraft mission are given in table 1 [1]. These numbers are very general, since no two missions are exactly alike. However, these data points can serve as a baseline to determine whether or not a valve could have potential applications in space.

Unfortunately, no commercial MEMS valves appear to be able meet both the performance and reliability requirements usually set out by NASA. With a little thought, most MEMS designs will fare well against shock, vibration, and radiation. However, either the temperature or the leak rate requirements knock these devices out of the running. Therefore, JPL has undertaken the development of a MEMS valve that will have a low leak rate, be impervious to particulates, and survive the punishments of both launch and space travel, yet still perform upon reaching its final destination [2].

DESIGN

Larger, commercially available diaphragm valves provided the baseline for the design of this valve. Figure 1 shows examples of some actual diaphragm and seat parts. Schematic cross-sectional views are given in figure 2a,b. The stand-alone device has a square footprint of 1.6 cm on a side, and should have a height of less than three millimeters. This may seem large for a MEMS device. However, since a valve's leak rate is mostly dependent on its sealing area, we feel that it makes sense to build a larger than typical micro-valve to satisfy the requirements for space applications.

The valve begins as three separate parts: the seat, the diaphragm, and the actuator. The base of the valve is known as the seat. This is the part that will interface with the rest of the micro-fluidic system. The seat contains the inlet and the outlet, as well as a set of seal rings around each opening inside the device. The center section of the valve is known as the diaphragm wafer. It has a circular corrugated diaphragm, with a circular boss in the center, covering both openings in the seat. The boss is either fully suspended by the diaphragm, or is also supported by four silicon suspensions. Finally, the actuator consists of a piezoelectric disk in a rigid housing. All three parts are bonded together using a metal-to-metal diffusion bond.

The valve is normally closed. The piezoelectric stack is forced into a slightly contracted position during the bonding process, to apply a large sealing force on the two openings. A simple Young's Modulus calculation can be used to determine the initial sealing force. Application of a voltage across the stack will cause it to contract even further, lifting the diaphragm away from the seat, as shown in figure 2b (not to scale). This creates a channel between the two openings, allowing for the passage of fluids. Because of the diaphragm, dead space is minimal.

Several design considerations have been implemented to try and satisfy the requirements for space applications. The most crucial is a low leak rate. The first and perhaps most important step towards that goals is, as mentioned before, the larger sealing area between the inlet and the outlet. Also, we apply the sealing force to both the inlet and the outlet of the valve. Finally, there is a large sealing area around both openings, preventing leakage to the environment. This seal is implemented through metal-to-metal diffusion bonding, a versatile low temperature process that typically yields better seals,

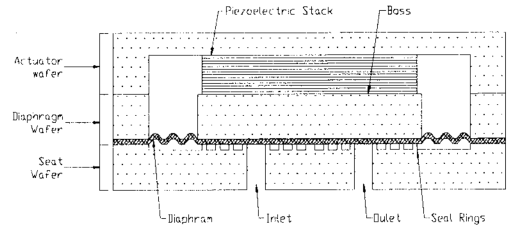


Figure 2a: Micro Valve Cross-section

capable of lower leak rates than many of the traditional techniques such as epoxy bonds typically seen in MEMS.

Immunity to particulates will be realized through the unique geometry of the sealing area. Instead of a flat sealing surface, we have implemented a series of closely spaced 20 μm high rings, expanding outward from both the inlet and the outlet. Because these rings are so many and so dense, they still provide a large sealing area. However, this configuration has the added benefit are being able to withstand small particles that may be in the flow. If the particles come in contact with the sealing surface, they will eventually be trapped in the valleys between the rings. Also, any single scratch that may occur will likely not create an open path from the inlet to the outlet, since it will only affect a limited number of rings.

Finally, this device moves away from the thermal actuation found in most commercial-off-the-shelf (COTS) valves [3] and instead uses a lead niobate piezoelectric disk. This way, the ambient temperatures seen by this valve will not have to be so tightly controlled. Piezoelectric actuation has not been utilized very often in miniature valves since it requires very high voltages in order to produce a substantial deflection. However, for space applications, this is not a fatal concern.

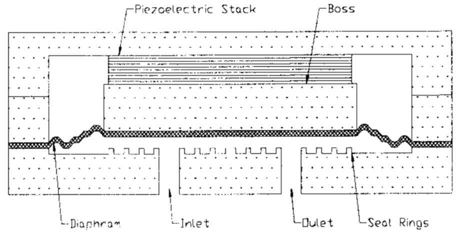


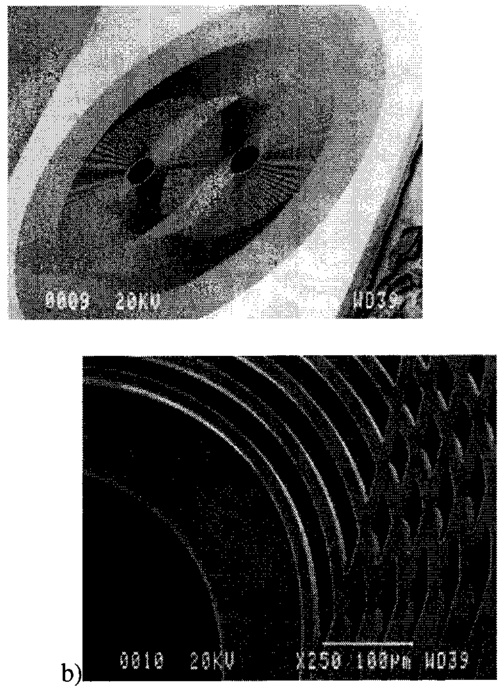
Figure 2b: Micro Valve Open Position

PROCESSING

Figure 3 and 4 shows some examples of finished parts for the JPL Micro-valve. The dimensions of both the diaphragm and seat are 16 mm by 16mm by 0.4 mm. The fabrication process relies heavily on a Deep-Trench Reactive Ion Etch (DRIE) to machine circular features into silicon. Presently, only seats and diaphragms have been fabricated and assembled. We feel it necessary to thoroughly test the seat-diaphragm structures before embarking on the design and implementation of the actuator.

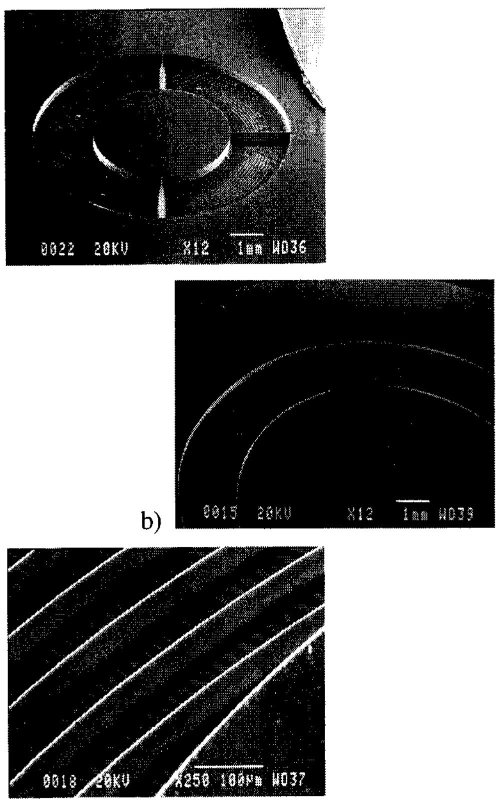
Both pieces are bulk micro-machined from n-type <100> silicon wafers. In order to create circular shapes, we use a novel DRIE technique [3]. This involves a series of alternating etching / passivation steps to achieve straight side-walls in silicon irrespective of the crystal plane. The etching is done by a combination of SF_6 and O_2 gasses, and the passivation by a combination of C_4F_8 and O_2 gasses.

We also use a low-pressure chemical vapor deposition (LPCVD) system to passivate the surfaces and fabricate the diaphragm. Finally, we use metal-to-metal diffusion bonding technique to assemble the parts. Bonding surfaces are metalized with a Ti/Pt/Au layer, and then held under high temperature and pressure to create a single diffused layer, thereby bonding the two pieces



a)
b)

Figure 4: SEMs of Seat Wafer
a) Inlet and outlet
b) Close up on seat



a)
b)
c)

Figure 3: SEMS of Diaphragm Wafer
a) Supported diaphragm
b) Suspended diaphragm
c) Close up of corrugation

The process for fabricating the seat-diaphragm assembly is outlined bellow.

1) First, seal rings and corrugations are etched into the seat and diaphragm wafers, respectively.
2) Patterning and DRIE etching through from the backside to fabricate the inlet and the outlet.
3) A low-stress 1um thick silicon nitride membrane is grown over all surfaces of both wafers.
4) Boss is released using DRIE etching from top of diaphragm wafer.
5) Next, metal is evaporated onto the bonding surfaces and patterned to create bonding areas.
6) The backside of the diaphragm wafer is patterned an etched to release the boss.
7) The wafers are bonded.

For the actuator, we intend to use a silicon housing with a lead niobate piezoelectric disk. Metalized visa will need to be etched through the housing to make electrical contacts. This piece will also be bonded to the seat-diaphragm assembly through a metal-to-metal diffusion process.

TESTING

Mating MEMS systems to testing apparatus has unexpectedly proven to be one of the larger challenges to this project. Traditional methods of plumming gasses to a valve and measuring flows are too bulky to work here. New couplings and measurement techniques needed to be developed to interface the micro and macro worlds.

Figure 5 shows the preliminary testing apparatus in schematic and reality. The valve is mounted onto a metal plate from which the inlet and outlet holes could easily be accessed. Air pressure at the inlet can be accurately varied using a series of gauges and regulators. The total volume of flow can be measured at the output. This and a timer are used to determine flow rate.

Preliminary tests include measuring the open flow rate vs. inlet pressure, and the force necessary to stop flow verses inlet pressure. Typical results are shown in table 2. The next step with this apparatus will be to improve the flow rate measurement scheme to determine the leak rates for given inlet pressures and sealing forces.

CONCLUSION

Micro and miniature fluidic systems have a broad range of applications both in research and in industry. NASA has a keen interest in reducing the size and mass of its fluidic systems, both in science instruments and in spacecraft subsystems such as propulsion. Quality MEMS valves will be vital to micro-fluidics. They are also the most difficult problem to solve.

The space environment is very unique, as are the kinds of tasks that people actually wish to accomplish in space. Mass is at a premium, and cost efficiency takes a back seat to performance. If MEMS can make a name for itself anywhere, it will be in the space industry. At JPL, we are attempting to blend simple innovations with proven configurations in order to produce the best possible valve for space applications.

The research described in this paper was performed by the Center for Space Microelectronics Technology, Jet Propulsion Laboratory, California Institute of Technology, and was sponsored by the National Aeronautics and Space Administration, Office of Space Science. We would also like to thank Larry Ruple and Steven Vargo for their technical support.

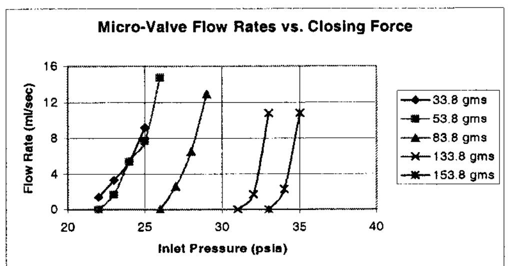
REFERENCES

[1] Mueller, J., "Thruster Options for Microspacecraft: A Review and Evaluation of Existing Hardware and Emerging Technologies", *33rd AIAA/ASME/SAE/ASEE Joint Propulsion Conf.*, Seattle, WA, July 6-9, 1997, AIAA 97-3058.

[2] Tang, W.C., et al "MEMS Micro Valve for Spacecraft Propulsion and Organic Material Sensors", *GOMAC '98 Micro-Systems and Their Applications Conference*, March 18, 1998

[3] Barth, P. W., "Silicon Microvalves for Gas Flow Control", *The 8th International Conference on Solid State Sensors and Actuators, and Eurosensors IX*, Stockholm, Sweden, June 25-29, 1995, pp 276-279.

Table 2: Experimental Data on Micro-Valve



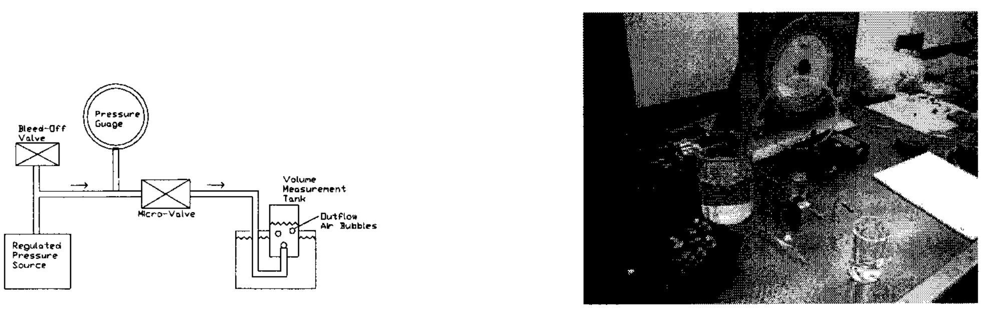


Figure 5: Schematic and Actual Photograph of Test Setup

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Space Applications For Micro Valves

NASA has identified the silicon micro valve as a key enabling technology for the insertion of MEMS in miniature space instrument. A silicon micro valve has a wide variety of applications, including the following:

- Micro Instrumentation for Insitu Analysis
- Micro Propulsion
- Micro Biology and Medicine in Space
- Miniature Vacuum Systems

Requirements For Micro Valves

The minimum requirements for a micro valve for micro propulsion applications are shown below. Leak rate must be very small since there is so little fuel. Requirements vary from mission to mission.

Leak Rate	< 0.3 scc/hr Helium
Acutation Speed	< 10 milliseconds
Inlet Pressure	0 – 400 psia
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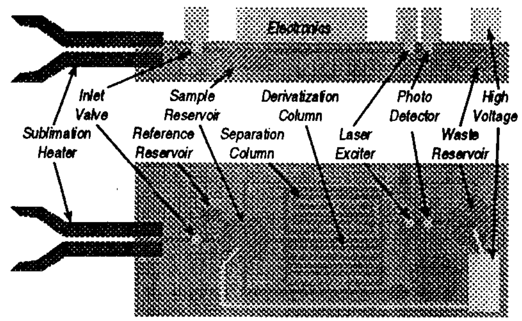
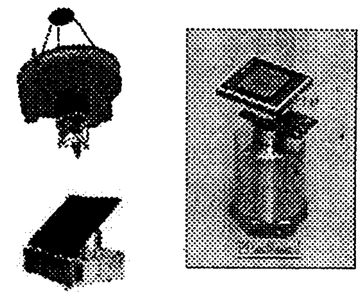
Vibration	31.5 G_{rms} for 3 min
Temperature	-120 °C to 200 °C
Radiation	50 krad/year
Particulates	< 5.0 micron

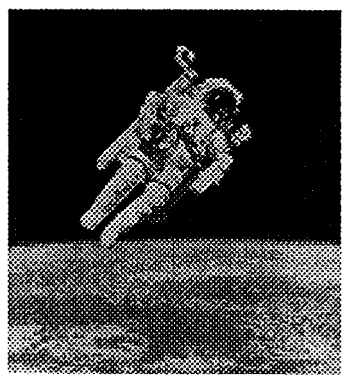


Capillary Electro Phoresis System for Life Detection (NASA JPL,U.C. Berkeley, Scripps)

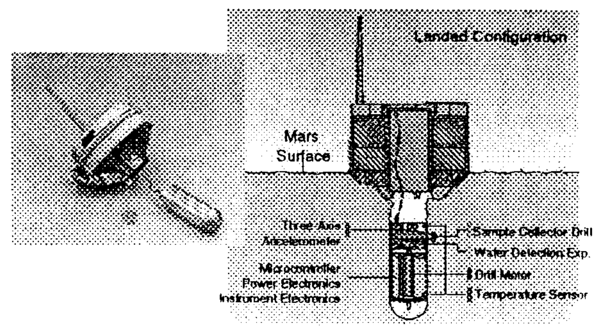
Could be fabricated on a Silicon Chip with a high performance Silicon Micro Valve



NASA JPL Micro Spacecraft Concepts & Solid Sublining Micro Thruster (Pictured with Redwood Systems Micro Valve)



NASA Medical and Biological Monitoring and Control in Space



NASA JPL Mars MicroProbe

Water Detection below Martian Surface

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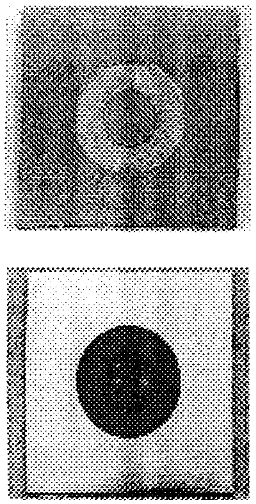
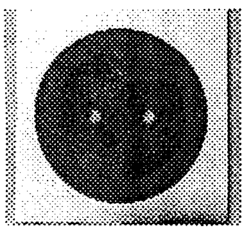


Diaphragm and Seat Parts for Design 1



Seat for Design 2

JPL Micro Valve Design and Operation

Larger, commercially available diaphragm valves inspire the design of this valve. The design is extremely general, and with slight modifications can be used as a proportional valve or regulator, isolation valve, or check valve.

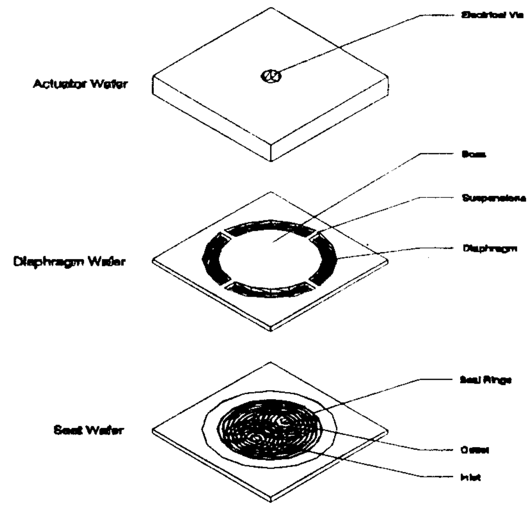
The valve begins as three separate parts: the seat, the diaphragm, and the actuator, as shown on the right. The base of the valve is known as the seat, which contains the inlet and the outlet, as well as a set of seal rings around each opening inside the device. The center section of the valve is the diaphragm wafer. It has a circular corrugated diaphragm, with a circular boss in the center, covering both openings in the seat. Finally, the actuator consists of a piezoelectric disk in a rigid housing.

The valve is normally closed. The piezoelectric stack is forced into a slightly contracted position during the bonding process, to apply a large sealing force on the two openings. Application of a voltage across the stack will lift the diaphragm away from the seat. This creates a channel between the two openings, allowing for the passage of fluids.

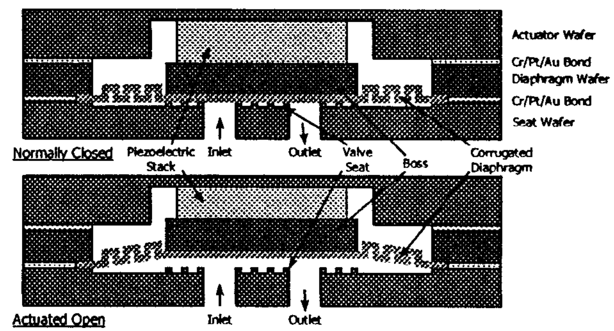
Several design considerations have been implemented to try and satisfy the requirements for space applications. The most crucial is a low leak rate. The first step towards that goals is the larger sealing area between the inlet and the outlet. Also, we apply the sealing force to both the inlet and the outlet of the valve. Finally, there is a large sealing area around both openings, preventing leakage to the environment.

Immunity to particulates will be realized through the unique geometry of the sealing area. Instead of a flat sealing surface, we have implemented a series of closely spaced 20 μm high rings, expanding outward from both the inlet and the outlet. Because these rings are so many and so dense, they still provide a large sealing area. However, this configuration has the added benefit are being able to withstand small particles that may be in the flow. If the particles come in contact with the sealing surface, they will eventually be trapped in the valleys between the rings. This design also helps reduce the leak rate because the progressive pressure decreases that occur between seal rings. Finally, any single scratch that may occur will likely not create an open path from the inlet to the outlet, since it will only affect a limited number of rings.

Finally, this device moves away from the thermal actuation found in most commercial-off-the-shelf (COTS) valves and instead uses a lead niobate piezoelectric disk. Piezoelectric actuators generally have a larger force densigy than comparaple bimetallic or shape memory schemes. Also, the ambient temperatures seen by this valve will not have to be so tightly controlled.



JPL Micro Valve Assembly Drawing



Valve Cross Section in Closed and Open Positions

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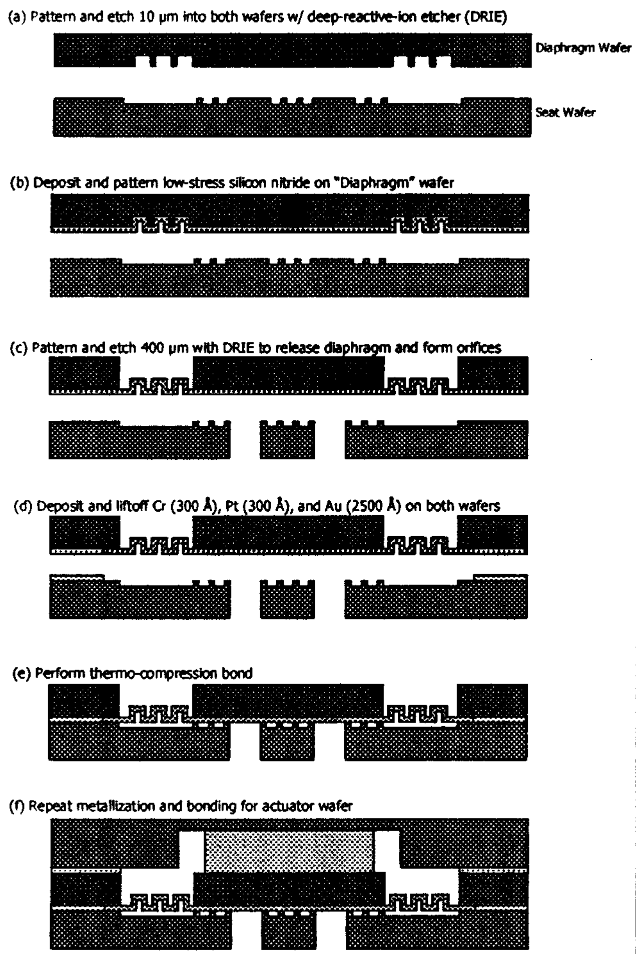


Fabrication Steps for JPL MEMS Micro Valve

JPL Micro Valve Fabrication

Presently, only seats and diaphragms have been fabricated and assembled. We feel it necessary to thoroughly test the seat-diaphragm structures before embarking on the design and implementation of the actuator.

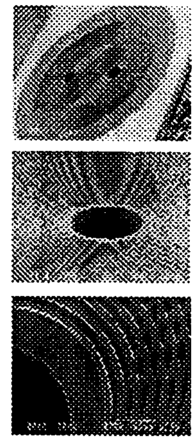
Both pieces are bulk micro-machined from n-type <100> silicon wafers. In order to create circular shapes, we use a novel DRIE technique. This involves a series of alternating etching / passivation steps to achieve straight side-walls in silicon irrespective of the crystal plane. The etching is done by a combination of SF_6 and O_2 gasses, and the passivation by a combination of C_4F_8 and O_2 gasses.

We also use a low-pressure chemical vapor deposition (LPCVD) system to passivate the surfaces and fabricate the diaphragm. Finally, we use ametal-to-metal thermo-compression bonding technique to assemble the parts. Bonding surfaces are metalized with a Cr/Pt/Au layer, and then held under high temperature and pressure to create a single diffused layer, thereby bonding the two pieces.

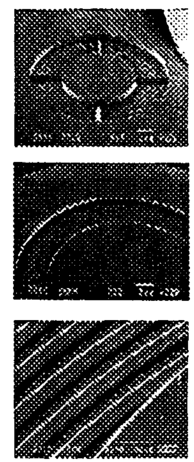
The process for fabricating the seat-diaphragm assembly is outlined below.

A) First, seal rings and corrugations are etched into the seat and diaphragm wafers, respectively.
B) A low-stress 1um thick silicon nitride membrane is grown over the corrugations of the diaphragm wafer.
C) Boss is released using DRIE etching from top of diaphragm wafer. A similar process is also used to etch the inlet and outlet into the seat wafer.
D) Next, metal is evaporated onto the bonding surfaces and patterned to create bonding areas.
E) The wafers are bonded.
F) A similar process will be used to fabricate and assemble the actuator onto the boss and seat.

For the actuator, we intend to use a silicon housing with a lead niobate piezoelectric disk. Metalized vias will need to be etched through the housing to make electrical contacts. This piece will also be bonded to the seat-diaphragm assembly through a metal-to-metal thermo-compression process.



Seat Parts



Diaphragm Parts

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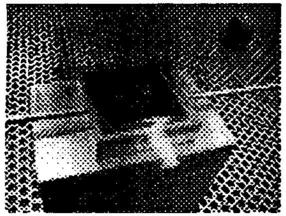
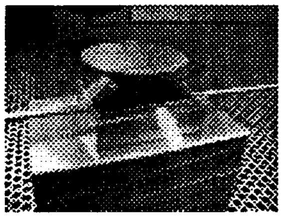
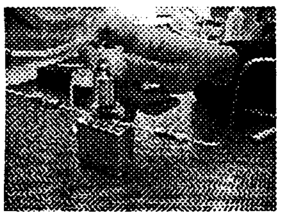


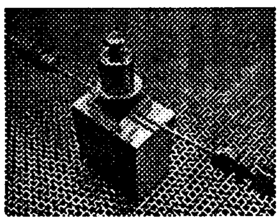
Valve under Kapton Tape



Valve and Weight Stand

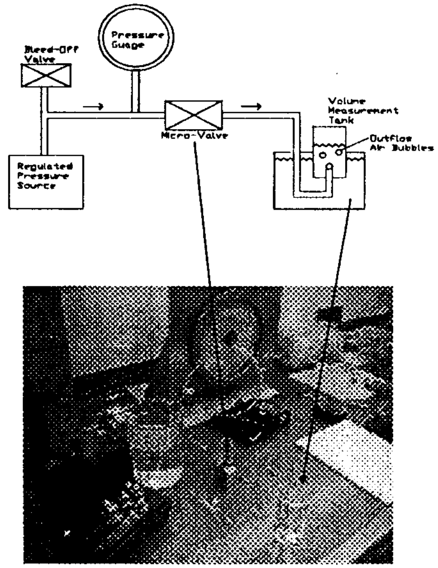


Application of Weight (to apply sealing force)

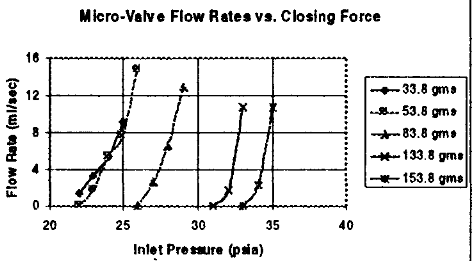


Sample Ready for Testing

Sample Preparation for Testing



Testing Station, Schematic and Actual



JPL Micro Valve Testing

Interfacing the macro and micro worlds is a common problem in the field of MEMS. Mating this MEMS system to a testing apparatus has unexpectedly proven to be one of the larger challenges to this project. Traditional methods of plumbing gasses to a valve and measuring flows are too bulky to work here. New couplings and measurement techniques needed to be developed to interface the micro and macro worlds.

Testing stations for this project have so far been studies in simplicity and speed. The valve is mounted onto a metal plate from which the inlet and outlet holes could easily be accessed. Air pressure at the inlet can be accurately varied using a series of gauges and regulators. The total volume of flow can be measured at the output. This and a precision timer are used to determine flow rate.

Preliminary tests include measuring the open flow rate vs. inlet pressure, and the force necessary to stop flow verses inlet pressure. Typical results are shown in the table. The next step with this apparatus will be to improve the flow rate measurement scheme to determine the leak rates for given inlet pressures and sealing forces.

Conclusions

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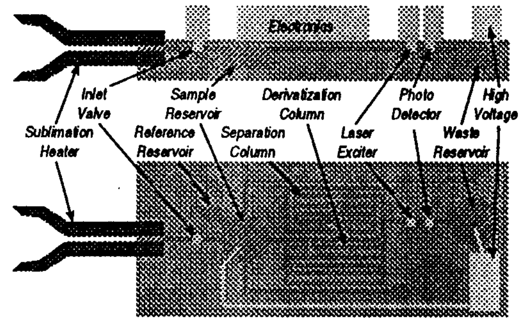
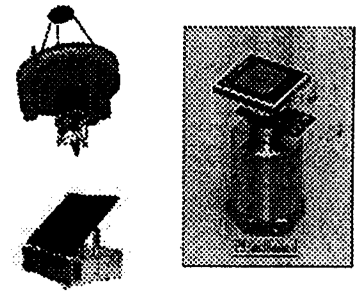
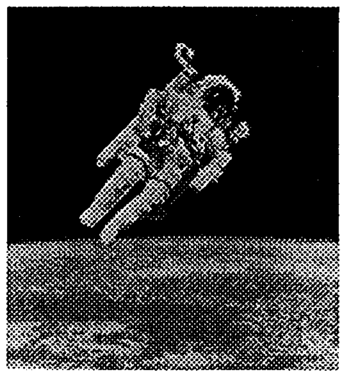


Capillary Electro Phoresis System for Life Detection (NASA JPL,U.C. Berkeley, Scripps)

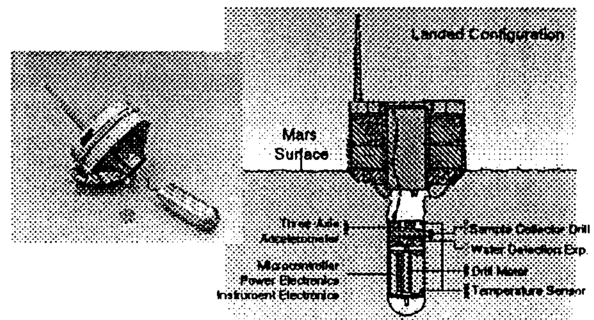
Could be fabricated on a Silicon Chip with a high performance Silicon Micro Valve



NASA JPL Micro Spacecraft Concepts & Solid Sublining Micro Thruster (Pictured with Redwood Systems Micro Valve)



NASA Medical and Biological Monitoring and Control in Space



NASA JPL Mars MicroProbe

Water Detection below Martian Surface

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